NAMRL-1123

USAARL
Serial No. 71-12

AD-717596

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ARMY – NAVY

Joint Report

U. S. ARMY AEROMEDICAL RESEARCH LABORATORY

NAVAL AEROSPACE MEDICAL RESEARCH LABORATORY

October 1970

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Bureau of Medicine and Surgery
MF12.524.004-5001BX5G

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29 October 1970

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SUMMARY PAGE

THE PROBLEM

The present problem is to compare performance limits and nystagmus induced by angular accelerations about the pitch and the yaw axes.

FINDINGS

Sinusoidal torsional oscillation (0.04 Hz, peak angular velocity ± 60 to ± 159 deg/sec)degraded subjects' performance of a compensatory tracking task because inappropriate nystagmic eye movements impaired visibility of the display. Responses to angular oscillation in yaw and pitch were compared. During angular motion in the pitch-forward direction the nystagmus frequency and slow phase velocity, and the consequent performance decrement, were significantly greater than during the pitch-back half cycle. No such asymmetry was found during oscillation in yaw where the nystagmus measures and error scores were similar to those obtained in the pitch-back half cycle. The poorer suppression of vestibular nystagmus during pitch-forward motion is attributed to the higher frequency and smaller amplitude of downbeating nystagmus. Angular oscillation in pitch induced motion sickness more rapidly than a comparable yaw-axis stimulus. This was probably caused by differences in the dynamic response of vertical and lateral canals and the greater mismatch of canal and gravireceptor signals during oscillation in pitch.

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INTRODUCTION

Pilot control of an aerospace vehicle, or a conventional aircraft, depends primarily upon visual cues that provide information about the behavior of the vehicle. When the pilot is deprived of vision, or visual acuity is degraded to such an extent that instruments cannot be read, then the control loop is broken and the safety of the vehicle and its occupants jeopardized.

Visual performance in the aerospace environment is influenced by many factors, of which this paper is concerned with but one; namely, the impairment of vision produced by involuntary nystagmic eye movements of vestibular origin. This is considered to be of special importance, for the visual disturbances produced by vestibular stimulation are commonly associated with illusory and disorientating sensations, which of themselves can lead to loss of control and aircraft accidents (3, 13, 14).

The nature of the nystagmus evoked by strong vestibular stimuli, when subjects attempted to see a visual target, has been quantified (8) and the concurrent impairment of visual acuity and performance of a psychomotor task requiring a visual input described (7). These studies were concerned predominantly with angular stimuli in yaw; however, it was found (9, 11, 12) that stimuli in pitch evoked a significantly greater nystagmic response, and hence acuity loss, when the angular acceleration acted in the forward direction than in the backward direction. No comparable asymmetry was observed for yaw-axis stimuli.

Previous studies of pitch-axis responses were restricted to measures of acuity loss obtained with Snellen letters (9) or dot targets (12) whereas the experiments here reported compared subjects' performance of a closed sequence control task when exposed to identical angular stimuli in the yaw and pitch axes. Though the psychomotor task employed can be regarded only as a simplified component of the flying task, it was considered that the demonstration of a behavioral decrement in a laboratory task of this type could be extrapolated more readily to the flight situation than the acuity measures already reported.

PROCEDURE

APPARATUS

A detailed description of the apparatus has been given in an earlier report (7). The angular stimulus was provided by the Human Disorientation Device (HDD) which was programmed to oscillate about a vertical axis. Sinusoids, with a periodic time of 25 seconds (f = 0.04 Hz) and peak angular velocities of ±60, 90, 120, and 159 deg/sec, were employed.

The subject was strapped to a seat within the HDD capsule, his head being supported in the vertical position close to the axis of rotation. It was possible to rotate the capsule of the HDD about a horizontal axis through 90 degrees so that the subject

could be moved from the normal vertical position to the left lateral position. It was thus possible to study the effect of sinusoidal oscillation in yaw (rotation axis coincident with z body axis) or in pitch (rotation axis concident with y body axis) (Figure 1).

The subject was required to perform a compensatory tracking task. A quasi-random signal deflected the vertical needle of a cross-pointer (ILS) aircraft instrument which was positioned 0.8 meter in front of the subject. The needle could be brought to the center, null position by movement in the anteroposterior direction of a short joy stick which was supported between the subject's legs in a position where the control could be operated without discomfort. Irrespective of the orientation of the subject relative to the axis of rotation, the tracking-task display was always positioned so that the needle was vertical (i.e., parallel to the rotation axis) and was deflected from the null position in a horizontal direction. Thus with the subject in either the vertical or lateral position the eye movements evoked by the angular oscillation would always tend to degrade visibility of the error display.

Localized illumination of the instrument display was provided by a small projector fitted with neutral density filters to give pointer luminances of 0.01, 0.1, and 1.0 f-L (0.034, 0.34, and 3.4 cd/m^2). No other illumination of the capsule was provided.

The accuracy of the subject's performance of the tracking task was obtained from the modulus error signal which was integrated over successive 1-second periods. Lateral (horizontal) and vertical eye movements were recorded by the conventional electro-oculographic technique. The angular velocity of the slow phase components of evoked nystagmus was measured from the graphical records, upon which were also displayed the integrated absolute error signal, the angular velocity of the HDD, and the tracking-task forcing function.

METHOD

The experimental procedure followed closely that employed in the earlier study (7). There was a 7-minute period of dark adaptation before the subject was allowed to practice the tracking task for 4 minutes with the HDD stationary. Performance was measured over the last minute of the practice period, and this value was used for subsequent comparison with measures obtained during vestibular stimulation. When the vertical canals were to be stimulated (angular oscillation in y body axis), the subject was moved to the left-ear down position at the end of the period of dark adaptation.

After the 4-minute practice period, oscillation of the HDD began and the subject resumed tracking. Eye movements and performance were recorded for at least five complete stimulus cycles before the HDD was brought to a stop.

Experiment I was carried out on six subjects who were exposed only to a sinusoidal oscillation in pitch (y body axis) with a peak angular velocity of $\pm$159 deg/sec. Each subject performed the tracking task with display luminances of 0.01 and 1.0 ft-L,

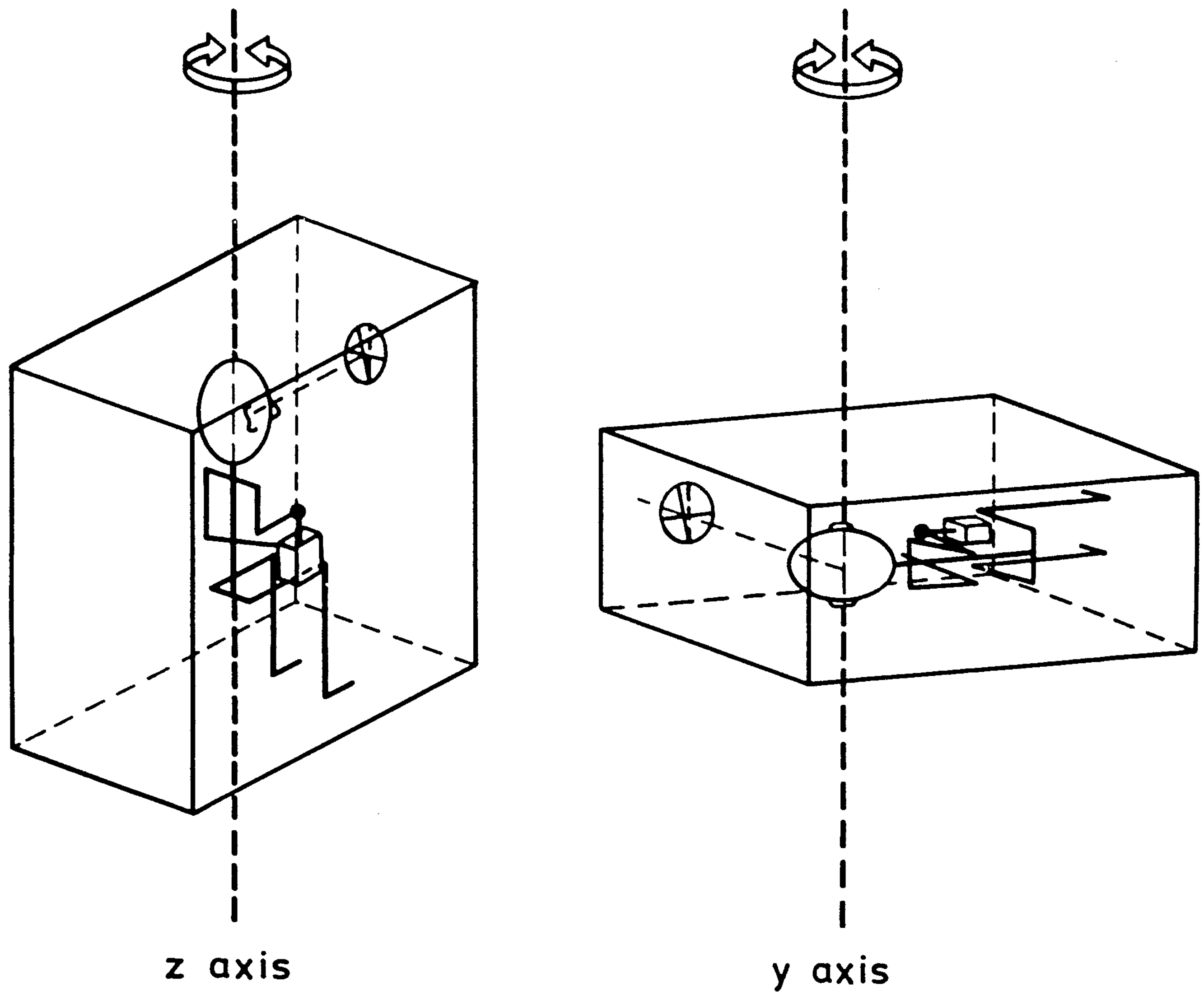

Figure 1

Diagrammatic representation of the positions of subject, within the capsule of the HDD, which were used to examine the response to oscillation in yaw (on left) and pitch (on right). The rotation axis and the needle of the instrument display, in its null position, were always Earth vertical.

the order of presentation of these two experimental conditions being alternated between subjects. Subjects also were oscillated in darkness to obtain measures of nystagmus without visual suppression.

Experiment II involved another group of six subjects, none of whom had participated in Experiment I. They each experienced six experimental conditions which involved sinusoidal oscillation ($f = 0.04$ Hz) at peak angular velocities of ±60, 90, and 120 deg/sec in both yaw (z body axis) and pitch (y body axis). The display luminance was held constant at 0.1 ft-L. The order of presentation of experimental conditions was randomized among subjects according to a Latin-square design.

SUBJECTS

Young men, either members of the laboratory staff or from the Naval Aviation Schools Command, were used as subjects. All were in good health without apparent abnormality of vestibular function.

RESULTS

EXPERIMENT I

The primary objective of this study was to investigate the effect of pitch-axis oscillation on tracking-task performance and nystagmus under stimulus conditions comparable to those of a previous study (7) in which only yaw-axis stimuli were used and each subject was exposed to sinusoidal oscillation at 0.04 Hz (peak angular velocity ± 159 deg/sec) for about 5 minutes at each of four display luminances. However, when an attempt was made to repeat the same test schedule with subjects in the left lateral position, so that the angular stimulus was to the vertical rather than the lateral canals, it was found that few subjects were able to complete the full test sequence. After the first or second stimulus condition subjects complained of nausea and exhibited the characteristic signs of motion sickness. As a result of these pilot experiments the duration of the test schedule was reduced; the period of exposure to the angular oscillation was halved, and only three luminance levels (0, 0.01, and 1.0 ft-L) were employed. Even so, five of the eleven subjects who were exposed to this attenuated schedule became sick and hence were not asked to complete the experiment.

Performance of Compensatory Tracking Task

Comparison of error scores obtained when the subjects were stationary with those recorded when they were exposed to the angular oscillation indicated that the vestibular stimulation brought about a substantial decrement in performance. The mean error scores averaged over five cycles for the six subjects (Figure 2) showed a biphasic periodicity at both display luminances. As found with the yaw-axis stimuli, performance of the tracking task was significantly ($P = .01$) worse at the low (0.01 ft-L) display luminance than with the brighter (1.0 ft-L) display. Peak decrement was associated with peak stimulus velocity and reflected the severe impairment of vision which the

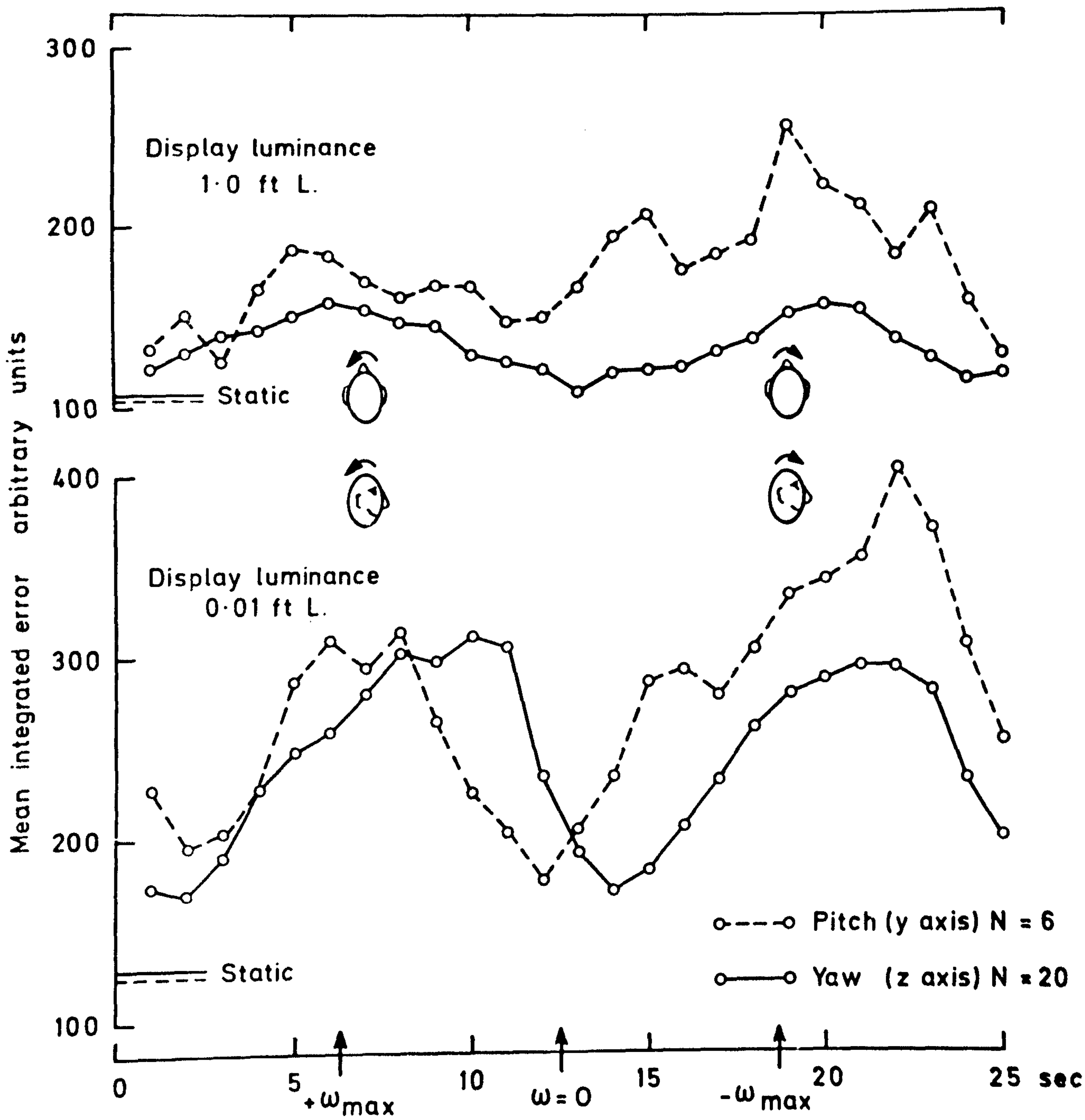

Figure 2

Effect of display luminance and axis of rotation on tracking-task performance during oscillation at 0.04 Hz (peak velocity ± 159 deg/sec). Each point is a mean 1-second integrated error score which for oscillation in pitch was averaged over five cycles for six subjects, and in yaw over ten cycles for twenty subjects.

subjects experienced during a substantial fraction of each half cycle. The performance measures were in agreement with the subjective reports of a more severe blurring vision during rotation in the pitch-forward direction than in the opposite direction. However, the difference in error between the pitch-forward and the pitch-back half cycles was not significant at the P = .05 level.

When the mean error scores obtained during oscillation in pitch were compared with those for yaw-axis stimulation, minor differences were apparent. The mean performance score during oscillation in pitch was higher than when the same angular stimulus was given in the yaw axis. However, significant differences between the two experimental conditions were not substantiated by a statistical test, primarily because of the use of dissimilar subject groups and high intersubject variability. The other feature, worthy of note, is the apparent shift of the maxima and minima of the error scores for pitch-axis stimulation relative to those obtained in the yaw axis. The shift of the cyclical waveform to the left is compatible with known differences in the long time constants (Π/Δ values) (6) of the vestibulo-ocular reflex for vertical and lateral canals. Such differences can readily account for the greater phase advance of the velocity of the compensatory eye movements, and hence tracking task error, associated with sinusoidal angular motion in pitch at 0.04 Hz.

Nystagmus

Electro-oculographic records of vertical eye movements taken during oscillation in pitch, obtained both in the dark and when tracking task display was illuminated, were not of the form anticipated from the severe blurring of vision reported by subjects during oscillation or from the records of lateral eye movements obtained in the earlier investigation of yaw-axis oscillation. Whereas the lateral eye movements evoked by angular oscillation in yaw showed a characteristic direction-changing nystagmus with a symmetrical sinusoidal modulation of slow component eye velocity, the vertical eye movements produced by oscillation in pitch were overtly different during angular motion in the forward and backward directions. As Figure 3 shows, rotation in a backward (CCW) direction in the dark produced reasonably well-defined nystagmoid eye movements, but when rotation was in the forward (CW) direction, the nystagmus was of high frequency, small amplitude, and irregular. Accurate measurement of eye velocity during rotation in a forward direction was thus impossible, probably because of the low pass characteristic (-3 dB at 35 Hz) of the recording system and its noise level. On superficial inspection, the electro-oculographic record obtained during rotation in a forward direction had the appearance of a random deviation of the eye without the characteristic sawtooth pattern of nystagmus. But this appearance belied the presence of small-amplitude, high-frequency eye movements which must have been responsible for the severe loss of visual acuity experienced by all subjects during this phase of the angular oscillation.

Figure 3 illustrates the manner in which illumination of the tracking-task display modified the nystagmic response. During rotation in a backward direction the reduction in amplitude and velocity of nystagmus, beating with slow phase down, was qualitatively

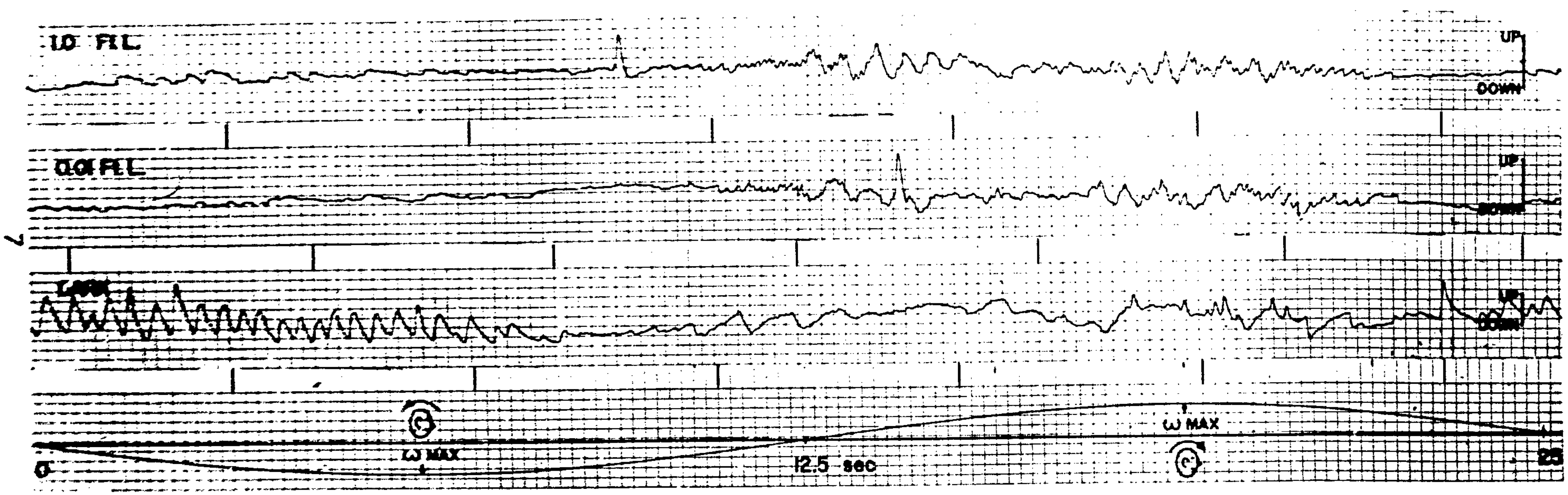

Figure 3

Modification by different levels of display illumination of the EOG record of vertical eye movements evoked by oscillation in pitch. Sample records from one subject over one stimulus cycle (0.04 Hz, ± 159 deg/sec).

comparable to that observed in yaw. However, during the other half of the cycle when nystagmus beat was slow phase up, the suppression produced by the visual stimulus was much less apparent. Comparison between the nystagmus in the dark and when the display was illuminated was impossible during the period of peak response, but the relative lack of suppression associated with display illumination could be discerned in those parts of the record adjacent to points of nystagmus reversal where the eye velocity was lower.

EXPERIMENT II

The high incidence of nausea and the inability to obtain quantitative measures of nystagmus during the whole of an oscillatory cycle when the vertical canals were stimulated indicated that, if responses in the yaw and pitch axis were to be adequately compared, weaker stimuli would have to be employed. Accordingly, a second experiment was carried out in which subjects were exposed to a sinusoidal angular oscillation with peak angular velocities of ±60, 90, and 120 deg/sec. Each subject performed the tracking task at one level of display luminance (0.1 ft-L) but at all stimulus intensities in both the vertical (yaw axis) and left lateral axis (pitch axis) positions. Figure 4 summarizes the data obtained from six subjects and shows mean tracking task errors and slow phase eye velocity, averaged at 1-second intervals over the 25-second stimulus cycle.

Performance of Compensatory Tracking Task

The biphasic modulation of performance previously observed with the ±159 deg/sec oscillation was still apparent at the lower stimulus intensities, although the magnitude of the performance decrement was proportionally decreased. The greater impairment of performance during pitch-forward angular motion than during pitch back, or during oscillation in yaw, is clearly shown in Figure 4, as is the phase advance of the pitch-axis errors with respect to those obtained with yaw-axis stimuli.

Statistical analysis was carried out on the error scores averaged for each subject over CW and CCW half cycles for each experimental condition. The group means of these half-cycle averages are plotted against peak stimulus velocities in Figure 5, and demonstrate the strong positive correlation between error score and stimulus intensity. However, the important feature is the appreciably larger performance decrement obtained during pitch-forward (CW) rotation than during pitch back, or CW and CCW rotation in yaw; at all stimulus intensities the mean half-cycle error scores were significantly greater (P = .01 by analysis of variance) than in the other three conditions. In constrast, performance during rotation in the CCW direction in pitch did not differ significantly from that obtained during the CCW half cycle in yaw and was only greater (P = .05) than the CW yaw values with the ±60 deg/sec and ±90 deg/sec stimuli.

Nystagmus

The dissociation of the responses to pitch-forward motion from those produced by

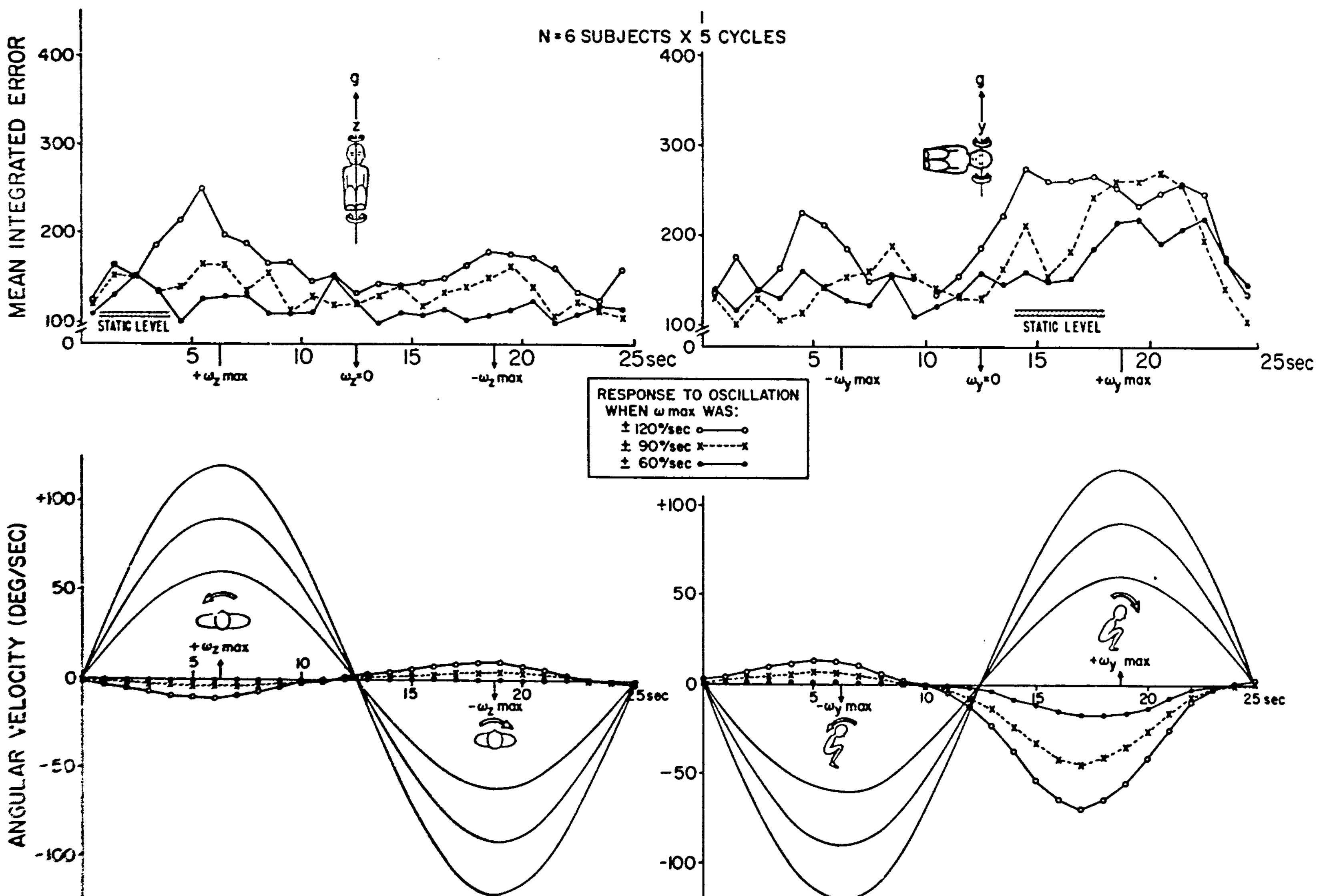

Figure 4

Comparison of error scores (upper half) and nystagmus slow phase velocity (lower half) during oscillation in yaw (left) and pitch (right). The stimulus, shown by the continuous line in the lower half of the figure, had a frequency of 0.04 Hz and peak angular velocities of ±60, ±90 and ±120 deg/sec. Display luminance was 0.1 ft-L. Each point is a mean value obtained from six subjects over five cycles.

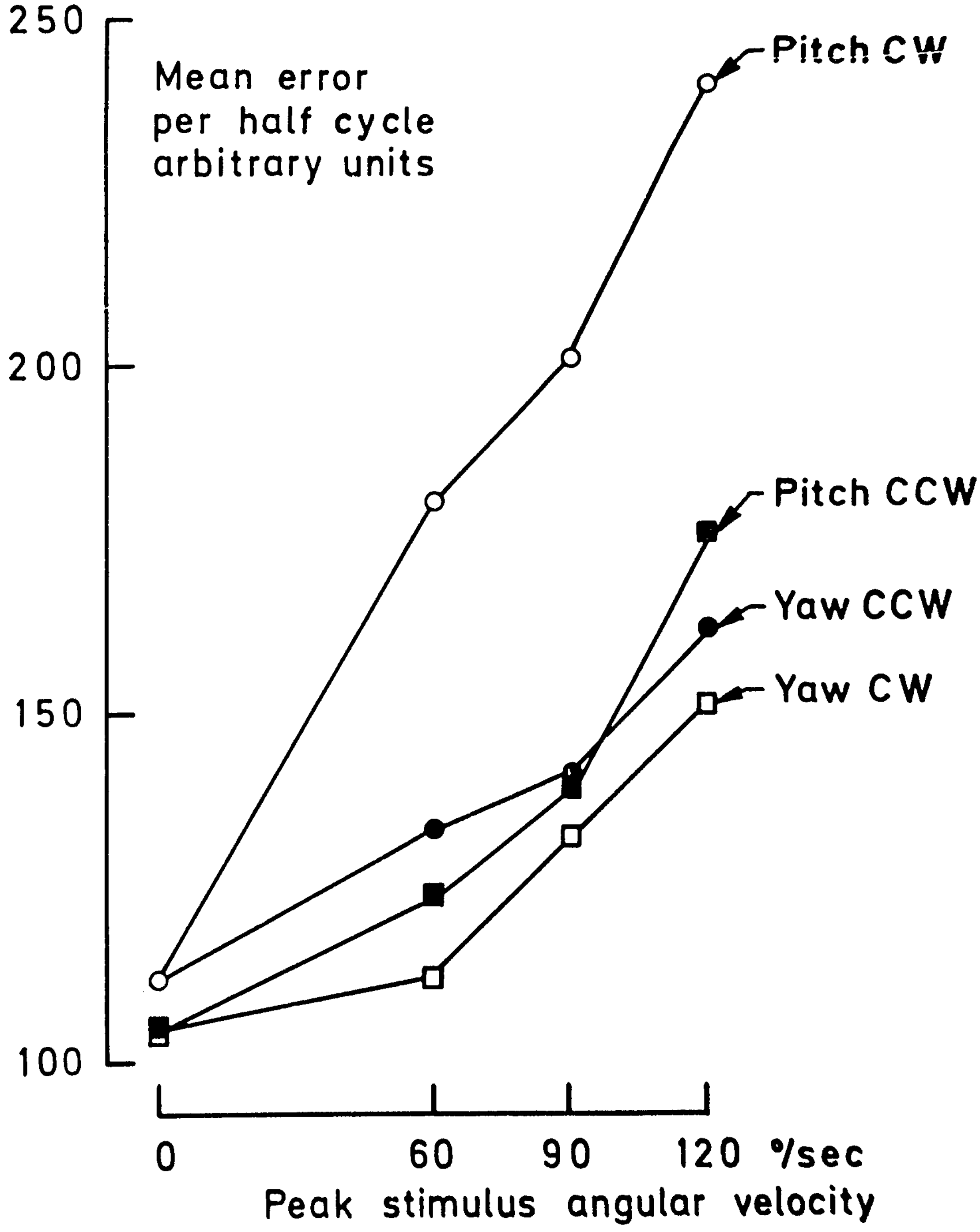

Figure 5

Relationship between tracking-task error and intensity of the stimulus, to illustrate the effect of the direction of angular motion and the axis of stimulation. With the exception of the "static" error scores at zero-stimulus velocity, each point is the error score averaged over five stimulus cycles for six subjects. Stimulus half cycles are separated; pitch CW and CCW correspond to angular motion of the subject in the pitch-forward and pitch-back directions, respectively.

pitch back and by yaw to the right and left, observed in the performance of the tracking task, was even more clearly demonstrated by the records of vertical and lateral eye movements. As an example, the electro-oculographic records of vertical and lateral eye movement obtained from one subject during sinusoidal oscillation (peak velocity $\pm$ 120 deg/sec) in pitch and yaw are presented in Figure 6. The vertical nystagmus during the pitch-forward half cycle had substantially greater amplitude and frequency than obtained during angular motion in the opposite direction. In contrast, the lateral nystagmus evoked by oscillation in yaw was of similar magnitude, in both half cycles, to the vertical nystagmus recorded during the pitch-back half cycle.

The velocity of the slow phase components of the nystagmic response was measured at 1-second intervals over five cycles and mean velocity curves assembled for the six subjects for each experimental condition (Figure 4, lower half). Eye velocity scores were also averaged for each half cycle, in the same manner as performance data, and plotted against stimulus intensity (Figure 7A). Both of these analytic procedures demonstrated the greater nystagmic response, at each stimulus intensity, during the CW rotation in pitch than in the CCW half cycle, and emphasized further the similarity of the responses recorded during yaw-axis oscillation with those produced by CCW rotation in the pitch axis.

Analysis of variance of mean eye-velocity scores revealed a significant difference ($P = .01$) between the pitch-forward condition and the other three experimental conditions at each stimulus intensity. No significant differences were established between the responses during pitch back and yaw CW and CCW half cycles. Likewise, measures of the frequency of nystagmus, taken over a 3-second period at the time of peak response in each half cycle, differentiated the response to pitch-forward motion from that observed during pitch-back and yaw-axis oscillation (Figure 7B).

The mean eye-velocity curves (Figure 4) provide a clear demonstration of the differing phase relationships, between response and stimulus, in the yaw and pitch axes. For oscillation in yaw, the mean phase advance (ϕ) of the compensatory eye movement, as judged by the time of zero crossings, was 14.4 deg; in pitch the mean phase advance was 27.4 deg. These measurements, made at a stimulus frequency of 0.04 Hz ($\omega = 0.251$ rad/sec), correspond to long time constants (T_1 or Π/Δ value) of the vestibulo-ocular system for stimuli in yaw and pitch of 15.6 seconds and 7.7 seconds, respectively. (A simple second-order system was assumed (17) where $\phi = 90^{\circ} - \text{arc tan } \omega T_1$.)

Comparison of mean error scores with the mean slow phase eye velocity during CW and CCW half cycles at the three stimulus intensities revealed a monotonic relationship between these two variables. When error scores were plotted against the logarithm of mean eye velocity (Figure 8), the values associated with the pitch-forward condition appeared as a continuation of the function established by the other three experimental conditions. It may thus be inferred that the high error scores obtained during angular motion in the pitch-forward direction were dependent solely upon the greater nystagmic response evoked by this angular stimulus, and that no essential difference existed between the impairment of performance wrought by vertical as opposed to lateral eye movements provided they were of comparable velocity.

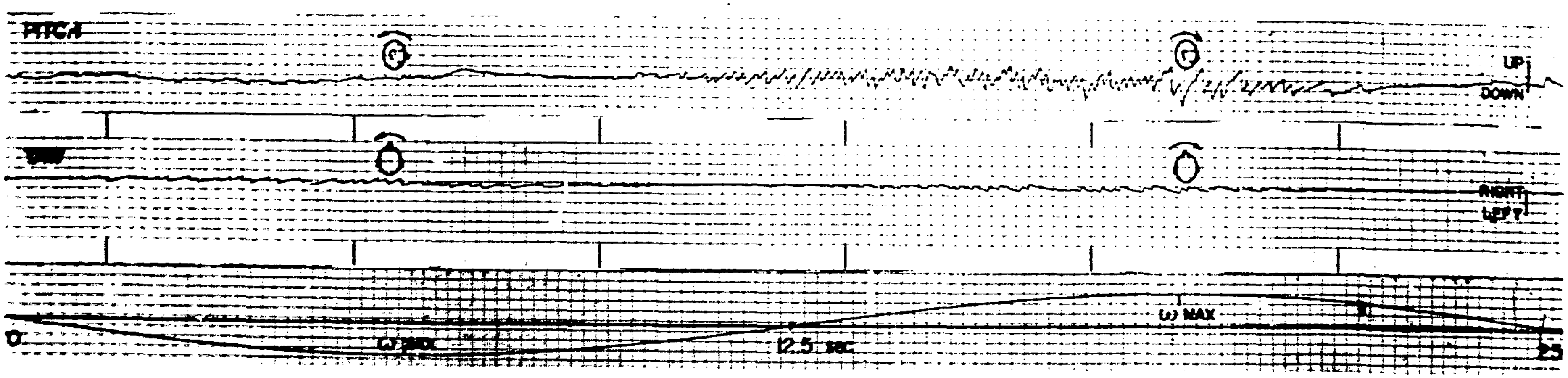

Figure 6

Sample record from one subject to illustrate vertical (upper) and lateral (lower) nystagmic eye movements evoked by a sinusoidal oscillation in pitch and yaw, respectively. The stimulus in each situation was a sinusoid of frequency 0.04 Hz and peak velocity of ±120 deg/sec.

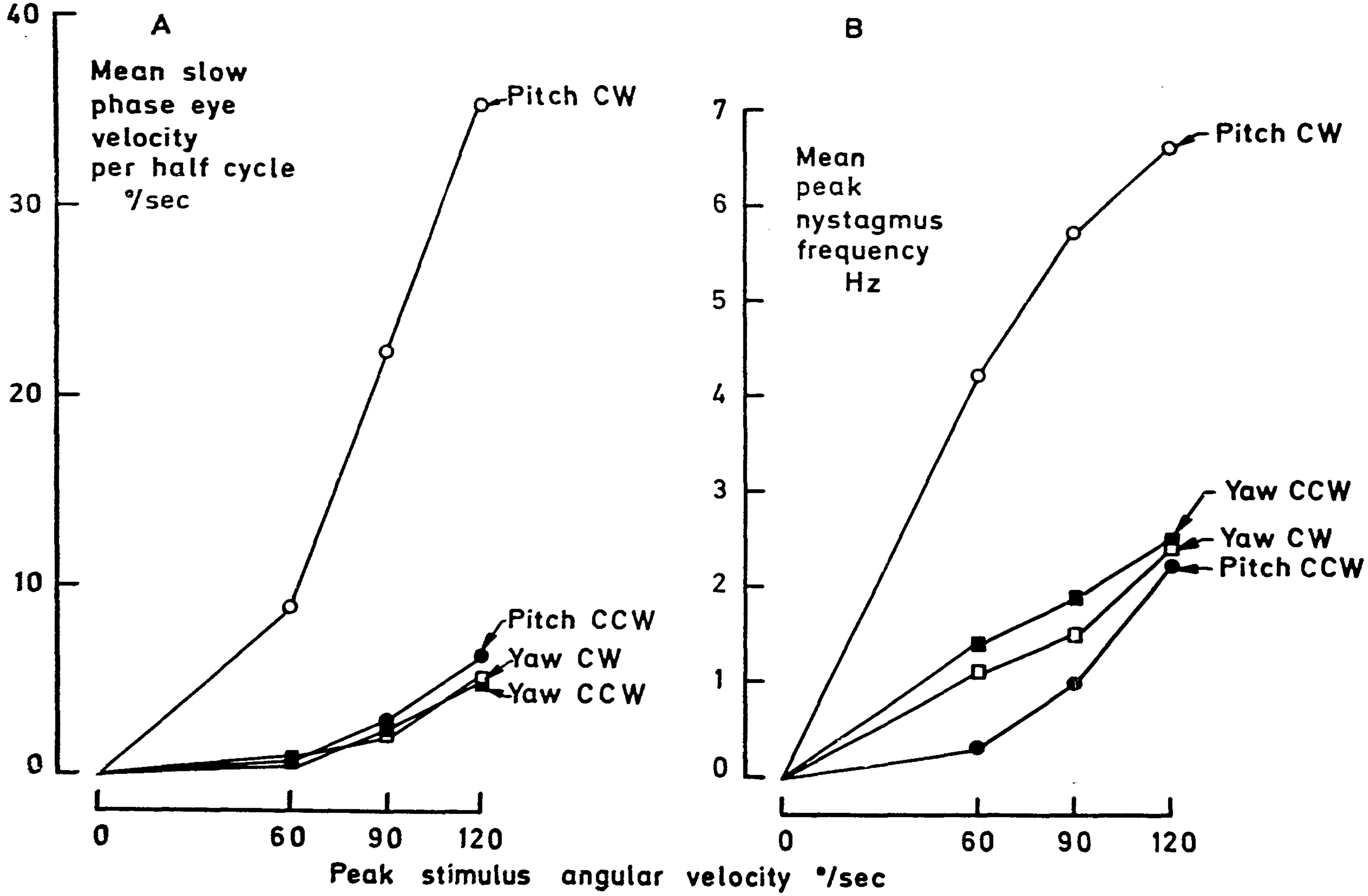

Figure 7

Slow phase velocity and peak frequency of nystagmus, related to intensity of sinusoidal stimulation, in subjects who were performing the tracking task. In A the eye velocity was averaged over five cycles in six subjects. In B the frequency of nystagmus was measured over a 3-second period at the time of maximum (peak eye velocity) response and averaged over five half cycles for the six subjects. The nomenclature of the stimulus half cycles is the same as in Figure 5.

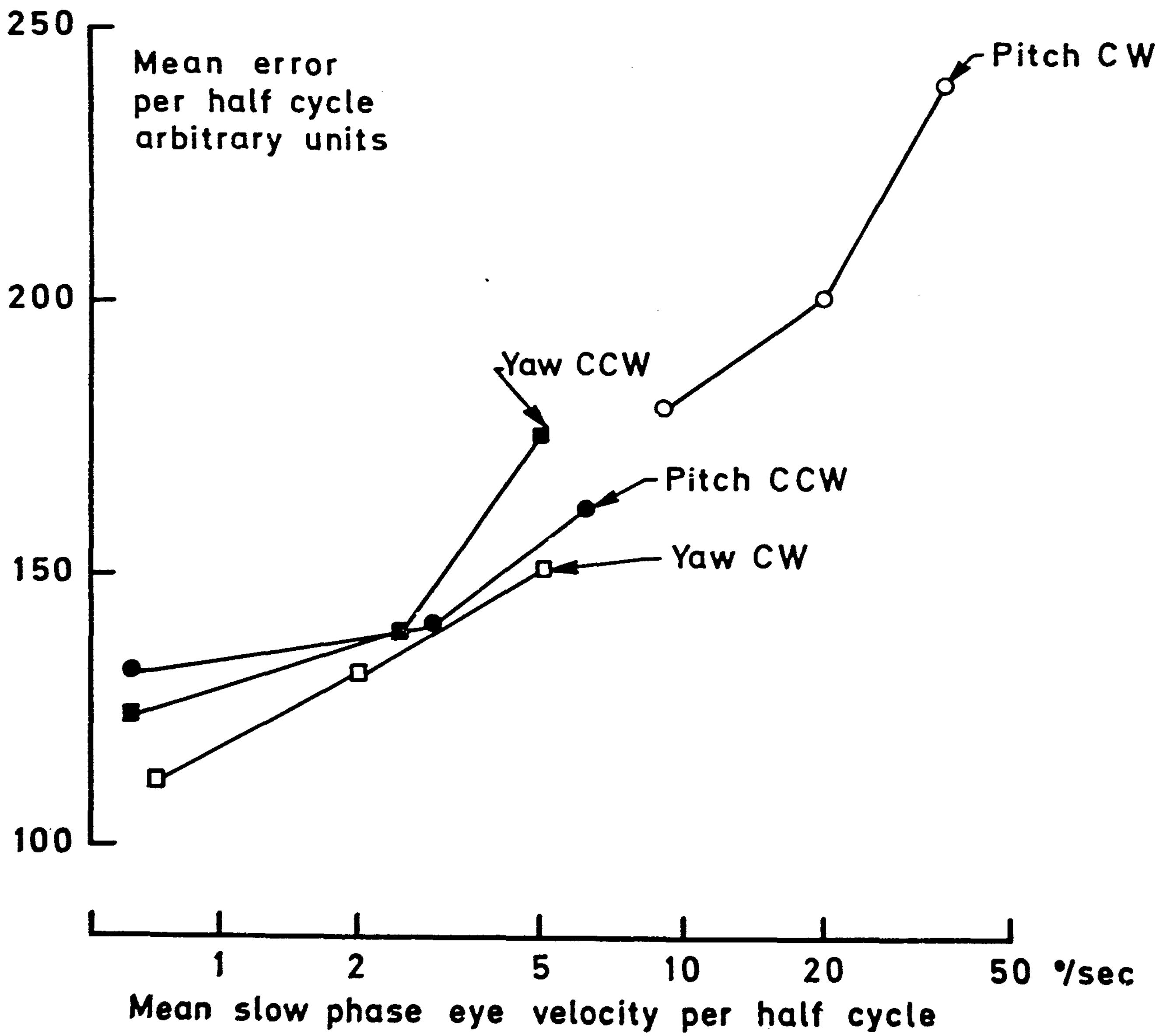

Figure 8

Relationships between tracking-task performance and nystagmus slow phase velocity. These graphs are assembled from the mean half-cycle scores depicted in Figures 5 and 7A; the nomenclature of the stimulus half cycles is the same as in these figures.

DISCUSSION

The changes in performance on the compensatory tracking task observed in the different experimental conditions can be attributed to impairment of vision by inappropriate and incompletely suppressed nystagmic eye movements. As noted in an earlier study (7), the extent to which performance was degraded was closely related to the slow phase velocity of the nystagmus, though peak performance decrement occurred slightly after peak eye velocity due to the time taken for tracking error to accumulate. Nevertheless, mean error scores during the oscillatory cycle reflected the waxing and waning of eye velocity as well as the greater phase advance of the oculomotor response when the vertical canals were stimulated.

It is of interest that estimates of the long time constant (equivalent to the Π/Δ value of van Egmond et al. (6)) obtained from the phase error gave values which were close to these obtained in earlier studies (4, 15) where step velocity inputs were used. The long time constant of vertical and lateral canals, or more precisely the vestibulo-ocular reflex for stimuli in yaw and pitch, differed by a factor of two. The smaller value for the vertical canals implied less effective compensation at low frequencies to pitch stimuli than to those in yaw. The largest decrement in performance was associated with angular motion in the pitch-forward direction, a finding which was in agreement with the subjective reports of impairment in visibility of the display and with measurements of slow phase eye velocity. Reduction in the luminance of the tracking-task display was found to produce an impairment in performance for pitch-axis stimuli comparable to that observed in the yaw axis (7).

The differential nystagmic response observed during angular oscillation in the pitch axis is in accord with the findings of earlier studies. Guedry (9) and Hixson and Niven (12) have reported that in subjects who attempted to see an illuminated target, a greater nystagmic response was evoked by an angular acceleration in the pitch-forward than in the pitch-back direction. With constant angular-acceleration stimuli the velocity of the slow phase of the vertical nystagmus in the up direction was found by Hixson and Niven to be approximately twice the speed of the slow phase down nystagmus, whereas Guedry reported a five-fold difference between the up and the down responses. However, in the present study an even greater disparity was observed, with up/down ratios of mean slow phase eye velocities of 13.8, 7.6, and 5.6 at stimulus intensities of ± 60, 90, and 120 deg/sec, respectively. In darkness, angular stimuli have produced up-and-downbeating nystagmus of approximately equal slow phase velocity (9); it was only when the subject attempted to see an object which was fixed with respect to himself that the up and the downbeating nystagmus was of differing magnitude.

Now it is known (1) that the presence of any discernable structure in the visual field causes some suppression, or partial inhibition, of nystagmus so that the response is of lower velocity and shorter duration than that recorded in the dark. Accordingly, it is reasonable to attribute the difference in the up and the downbeating nystagmus to the greater suppression of the slow phase down response than of the slow phase up

nystagmus (10); yet no such differential suppression was apparent in the lateral nystagmus evoked by comparable angular stimuli in the yaw axis (7).

Why should slow phase up nystagmus be less susceptible to visual suppression than lateral nystagmus or slow phase down nystagmus? Guedry and Benson (10) attempted to explain the difference by the need to suppress downward lateral eye movements engendered by optokinetic stimuli during forward motion, such as walking, where visual cues associated with upward movement of the eyes are relatively infrequent. However, this functional explanation does not account for differences in the form of the nystagmus associated with pitch motion in the forward and backward directions. As illustrated by Figure 7B, the frequency of nystagmus was substantially higher when the slow phase was directed upward than downward, a feature also exhibited in darkness (10). Indeed it was the extreme rapidity and small amplitude of the recorded eye movements occurring during angular motion forward at 159 deg/sec that necessitated the use of weaker angular stimuli for the quantitative studies of vertical nystagmus.

There is evidence (1) that the extent to which inappropriate vestibular nystagmus is suppressed depends upon the quality of the retinal image of the object upon which the subject attempts to fixate. Thus the nystagmus recorded when Frenzel glasses are worn is less than that recorded in the dark, but is substantially greater than when the subject looks at a brightly illuminated target. Likewise, it has been shown that the luminance of a visual display is positively correlated with the suppression of nystagmus during oscillatory stimulation (11).

Now, it may be argued that the small-amplitude, high-frequency nystagmus evoked by pitch-down motion causes a greater degradation of the retinal image than nystagmus of comparable slow phase velocity but of larger amplitude. The quality of the retinal image is poorer during the high-velocity saccadic eye movements than during the slow phase component. Hence, when nystagmus is of high frequency, there is a greater loss of retinal image structure, and consequently less suppression, than when nystagmus is of a lower frequency and the number of saccadic eye movements per unit time is less.

The explanation for the differential suppression of up-and-downbeating nystagmus is incomplete without discussion of possible mechanisms for the different character of the eye movement engendered by angular motion in the backward and forward directions. These may be the manifestation of a differing neuromuscular organization of oculomotor mechanisms subserving vertical movements in the up-and-down directions, a view which receives some support from the demonstration of more accurate pursuit eye movements and better dynamic visual acuity in the up than in the down direction (5). However, it is possible that the small amplitude of the slow phase up nystagmus is brought about by the need to restrict the vertical motion of the eye before the iris is occulted by the upper lid, the upward movement of which tends to lag the eye movement (2). Such limitation of upward displacement becomes more important as the speed of the eye movement increases, but to achieve a high slow phase velocity with small

amplitude eye movements the frequency of saccadic beats must also be raised. In contrast, with movement of the eyes in the downward direction, there is no restriction of vision by the lower lid until the eye has moved through an arc of 10 to 20 degrees; so, it is not to be expected that vestibular nystagmus with slow phase down would have the small amplitude and associated high frequency of that which is seen to occur when the slow phase is directed upward.

Torsional oscillations have been used quite extensively to study lateral (horizontal) semicircular canal responses, and it is generally considered that this type of stimulation does not readily engender motion sickness (16). The results of the present and earlier experiments, where subjects were exposed to relatively intense (± 159 deg/sec) stimuli in yaw, endorsed this view. However, it was apparent that when the subject was placed in the left lateral position and exposed to the same oscillatory stimuli, the signs and symptoms characteristic of motion sickness were rapidly induced. Even in Experiment II where less intense stimuli were employed, subjects were still troubled by "stomach awareness" or nausea when the oscillation was in pitch (y body axis). [redacted] Furthermore, symptoms were the more troublesome when the test was carried out in darkness than when the instrument display was illuminated and the tracking task had to be performed.

An explanation for the greater incidence of sickness associated with oscillation in pitch as opposed to yaw rests on the proposition that the former is associated with a greater disparity of sensory information than the latter. In everyday life, angular movements in pitch of the head and body are normally associated with a changing orientation to gravity. But the subject placed in a left lateral position on a turntable experiences no comparable stimulation of otolith organs or gravireceptors during angular motion of the table. Thus there is a mismatch between the actual sensory inflow from vestibular and other mechanoreceptors and that which the subject expects when the vertical canals are stimulated by angular motion in pitch. The presence of sensory mismatch is a common feature of stimulus situations that evoke sickness and must be regarded as a factor of prime etiological significance (18).

At the frequency of stimulation employed, the neural signal from the canals was phase advanced upon stimulus velocity; hence, the sensation of turning would tend to conflict with the subject's perception of angular motion derived from other cues, such as the changing radial acceleration and noise from the drive mechanism. It is suggested that such a mismatch between information from canals and from other sensory receptors would be the more severe when the subject was oscillated in pitch than in yaw. Not only was phase error greater, as revealed by the nystagmic response, but the subject was also exposed to a larger radial acceleration gradient and thus better able to sense the speed of rotation by nonotolithic receptors.

CONCLUSIONS

The practical implications of these findings to aerospace operations rests on the impairment of vision likely to be experienced by air crew who receive strong stimuli

to the semicircular canals, as a result of angular motion of the vehicle, pressure changes within the middle ear (alternobaric vertigo), or pathological processes. Irrespective of the mode in which canal receptors are stimulated, if the stimulus is sufficiently strong, nystagmus will be engendered, which will degrade the aviator's ability to see instruments within the aircraft and hence his ability to perform those tasks where visual displays are of prime importance.

Loss of vehicular control may result when control responses are based on false perceptions of the vehicle orientation; i.e., the pilot suffers from spatial disorientation. But, it must be recognized that vestibular signals, apart from engendering false sensations, can produce inappropriate eye movements that can seriously impair the only sensory channel through which veridical orientational cues are obtained. Blurring of vision has been described as a feature of certain disorientation incidents (3, 13); under certain conditions it is probably the most important single factor which turns an incident into an accident.

The present investigation has shown that angular stimuli in both yaw and pitch axes can engender nystagmus which cannot be fully suppressed by volitional mechanisms. However, it is the vertical nystagmus produced by pitch-forward angular stimuli that is the least susceptible to visual suppression and hence produces, for a given stimulus intensity, the greatest impairment in visual performance. Although in the flight environment sustained angular accelerations in pitch are less common than those in yaw and roll, nevertheless, during abnormal flight maneuvers (14), or escape procedures (12), personnel may be exposed to angular stimuli in the pitch axis. If the motion should be in the pitch-forward direction, there will be a greater decrement in visual performance than when the same angular stimulus acts in the pitch-back direction or in the yaw axis.

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Unclassified
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) Naval Aerospace Medical Research Laboratory Naval Aerospace Medical Center Pensacola, Florida 32512	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP N/A

3. REPORT TITLE

COMPARISON OF TRACKING TASK PERFORMANCE AND NYSTAGMUS DURING SINUSOIDAL OSCILLATION IN YAW AND PITCH

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

Alan J. Benson and Fred E. Guedry, Jr.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
29 October 1970	21	18

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S) NAMRL-1123
b. PROJECT NO. MF12.524.004-5001BX5G c. d.	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) USAARL Serial No. 71-12

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
Joint report with U. S. Army Aeromedical Research Laboratory, Fort Rucker, Alabama	

13. ABSTRACT

Sinusoidal torsional oscillation (0.04 Hz, peak angular velocity ±60 to ±159 deg/sec) degraded subjects' performance of a compensatory tracking task because inappropriate nystagmic eye movements impaired visibility of the display. Responses to angular oscillation in yaw and pitch were compared. During angular motion in the pitch-forward direction the nystagmus frequency and slow phase velocity, and the consequent performance decrement, were significantly greater than during the pitch-back half cycle. No such asymmetry was found during oscillation in yaw where the nystagmus measures and error scores were similar to those obtained in the pitch-back half cycle. The poorer suppression of vestibular nystagmus during pitch-forward motion is attributed to the higher frequency and smaller amplitude of downbeating nystagmus. Angular oscillation in pitch induced motion sickness more rapidly than a comparable yaw-axis stimulus. This was probably caused by differences in the dynamic response of vertical and lateral canals and the greater mismatch of canal and gravireceptor signals during oscillation in pitch.

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Vestibular stimulation						
Compensatory tracking						
Human factors						
Aviation						
Vision						
Rotation						

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